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Citation for published version:

Thew, I, Sutherland, A & Theodossopoulos, D 2012, 'Structural response of drystone Iron Age brochs', *Structures and Buildings*, vol. 166, no. 6, pp. 316-324. <https://doi.org/10.1680/stbu.11.00056>

Digital Object Identifier (DOI):

[10.1680/stbu.11.00056](https://doi.org/10.1680/stbu.11.00056)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Structures and Buildings

Publisher Rights Statement:

© ICE Publishing, 2012. Thew, I., Sutherland, A., & Theodossopoulos, D. (2012). Structural response of Drystone Iron-Age Brochs. *Proceedings of the ICE - Structures and Buildings*, 166(6), 1-9[1100056]doi: 10.1680/stbu.11.00056

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Structural response of drystone Iron Age brochs

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Understanding the structural behaviour of the drystone Iron Age brochs – prehistoric circular towers in northern Scotland – is essential for their investigation and conservation, but their chaotic collapse patterns have been studied in a fragmentary manner, primarily as historic evidence by archaeologists. The response of brochs to structural action was simulated by building two scale models and testing them in settlement, a possible source of failure. With the key features carefully reproduced and overall identical dimensions, the effect of variation of basal style between ground-galleried and solid-based, the two main types, was examined. The tests indicated that solid-based brochs can withstand a horizontal displacement at the wall head of twice that of ground-galleried types. The discussion of these tests provides further insight into the effect of the form and features, such as restricted openings or the intramural void. The conoid drystone form showed substantial strength, as large settlement was required to cause the failure of a scale model, suggesting that structural actions alone cannot cause collapse.

1. Introduction

The drystone broch conoid towers of the Scottish Highlands and Islands are very complex systems, by pre-historic standards (Armit, 2003). Study of their performance and construction process is important in assessing their evolution and development, as well as in planning compatible repairs or sensitive conservation and reconstruction projects.

A key design feature (Figures 1 and 2) is the double-leaf wall that tapers to form a truncated conoid, with very few openings. Local flagstone or volcanic rock was used, producing structures of considerable height (up to 15 m), so presumably their construction required a shared awareness of the stability problems when building to such a scale.

Currently there is a lack of comprehensive structural understanding of this typology (Barber, 2009). Most brochs are in a ruined state and only a few have been systematically excavated (Armit and Fojut, 1998; Harding, 2000; MacKie, 1974, 2002) or had their conservation state assessed (privately commissioned reports by consultants such as AOC Archaeology for Caisteal Grugaig, Clachtoll, Sallachy). The remains do not allow a clear assessment of the progress of the collapse, and often the study of the sequence shows many phases of post-collapse occupation. In



Figure 1. Dun Telve, Glenelg

this context, only archaeological reports exist that analyse the facts mainly in order to construct a chronological sequence.

This project is the first attempt to understand the design and stability of brochs using engineering methods and analysis of the



Figure 2. Mousa, Shetland (© RCAHMS (John Dewar Collection).
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performance, and is part of a collaborative research project with AOC Archaeology as the instigator and industrial partner. 1/15 models were built as they permitted the best and most practical simulation of the broch and their masonry bond. Investigating the effects of settlement, rather than dead load, was a relevant choice, as brochs are often built on problematic ground locations that could provide a clear failure directly correlated to its cause. The collection of qualitative observations during the construction of the model also offered valuable information on drystone technology.

The controlled application of vertical displacement simulates only one direction of settlement and does not include the beneficial effect of containment by the soil or a non-linear propagation of the failure. Two types were studied, the solid-based broch (Dun Telve type, Figure 1) and the ground-galleried broch (Gurness type, Figure 3), keeping the overall dimensions the same. Settlement was applied till ultimate collapse, to observe the mass of stone retained intact and the appearance of the ruins, but the observations were relevant to the performance of the prototypes only until the point when the settling portion detached completely. The large settlement confirmed the working hypothesis that the solid-based broch required more settlement to induce failure, and highlighted that structural actions alone are not capable of undermining their strength.

2. Stone features in a broch

Brochs are part of a strong tradition of drystone roundhouse building in Prehistoric Scotland that is believed to have lasted between 250 BC and 250 AD (Harding, 2004; MacKie, 2002).



Figure 3. Gurness, Orkney (© Crown Copyright: RCAHMS.
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Building traditions were already established from the earlier Atlantic roundhouses and chambered cairns in the middle of the previous millennium BC. What makes brochs unique within this tradition is their height and certain characteristics linked to scale. While roundhouses are straightforward single-storey buildings, brochs are far more complex multi-storey structures with some quite specific architectural features.

There are a few common features between all brochs that are discussed next and subsequently examined through the tests. Archaeologists debate about the relevance of some, such as the scarcement that is considered to support possible timber internal structures, but they have not been regarded in this study.

2.1 Height

Of the brochs still standing to a good height, indications show they would have stood to at least 10 m, with a number, among which Mousa (Figure 2), exceeding that (Mousa stands at 13.5 m). While the exact number of brochs that once stood to such a significant height is uncertain (MacKie, 2002), the massive scale of the basal remains at broch sites across Scotland suggest that hundreds were at least capable of supporting walls to something close to 10 m.

2.2 The intra-mural galleries

The double-leaf construction method is a very recognisable characteristic of the brochs. Either starting at the base (ground-galleries) or from a stone platform in the solid-based examples, two separate walls often run to the top of the building. Intra-mural stairs and galleries made from stone lintels span between the two walls. It has been suggested that these stone lintels acted as props between the two walls, keeping them apart, rather than the bracing effect of modern ties (as they do not bond deeply in the wall). Figure 1 shows this feature of the construction.

2.3 Profile

A distinguishing feature of all the brochs that still stand to a significant height is the profile. There is a distinct camber that gradually increases before decreasing and straightening (Figures 1 and 2).

2.4 A single-entrance passage

All brochs have only one opening in the outer wall, the entrance passage which, in some cases, is flanked by intra-mural cells (often called guard chambers). Above the entrance is a strong lintel stone which is often the largest stone present in the entire building.

2.5 Wall voids

On the inner wall, long and tall staggered openings are often present. They are among the poorest understood features as they appear to serve no obvious purpose (such as letting daylight into the building) and are difficult to explain in engineering terms as the discontinuity they create in the inner wall are clear areas of weakness within the fabric.

2.6 Basal style

Brochs broadly fall into two categories, the ground-galleried broch, where the galleries in the wall start at ground level (represented by Gurness, Figure 3), and the solid-based broch, where the continuous galleries start only after the first-floor level (Dun Telve, Figure 1). A third transitional category is very widely defined and was ignored for the purposes of this study.

2.7 Percentage-wall-base

A value commonly used by archaeologists to classify brochs is the percentage-wall-base value (PWB), the ratio of the overall external diameter ED taken up by the wall-base, first defined by MacKie (1974)

$$1. \quad \text{PWB} = \frac{(\text{ED} - \text{ID})}{\text{ED}} \times 100$$

where ID is the internal diameter (both mean values at the base). Table 1 summarises key data and PWB for the most intact surviving brochs. A more extensive discussion of the classifica-

tion and its problems can be found at (Fojut, 1981; Martlew, 1982), where it becomes clear that Mousa has a substantial base which may have been instrumental in its unique preservation and iconic status.

3. Selection of the case studies

The literature on brochs was reviewed on the basis of PWB and basal style. The different styles or intermediate cells have generated very important archaeological questions regarding origins, users' access to upper floors etc, and their effect on structural performance is expected to be quite crucial. A comparison between the two basal styles was made, by selecting two brochs of typical proportions and same PWB. After a parametric study of geometric and conservation data (principally MacKie, 2002, 2007) Dun Telve and Gurness were selected, additionally as they have their characteristic basal features intact, including intra-mural stairs and galleries.

3.1 Dun Telve

Dun Telve is one of a pair (together with Dun Trodden) of solid-based brochs in Glenelg, in West Scotland, surviving at a height of 10.22 m for around a quarter of its circumference and with ED = 18.2 m and PWB = 47% (Figure 1). Often cited by archaeologists as the most representative of all brochs (Curle, 1916), it is very well constructed and preserved; the central court is quite perfect, with a standard deviation of only 2 cm from a true circle (MacKie, 2002). The fine quality of stonework is attributable to the use of long rectangular blocks producing a tight drystone bond.

3.2 Gurness

While the broch of Gurness (Figure 3) is not as complete, with ED = 19.2 m and PWB = 46.0% it is a particularly large and impressive example of a ground-galleried broch. There is little evidence as to how high it originally stood; however, the scale of the base and quality of stonework (large oblong blocks) suggest it could support considerable fabric and it is not unreasonable to suggest a height between 8–10 m (MacKie, 2002). Internal partitions in flagstones have raised interesting questions about the use of the building, but since they have no load-bearing function they will not be considered.

Broch	ED: m	Wall thickness: m	Height: m	PWB: %
Mousa	15.1	4.8	13.26	64.4
Dun Carloway	14.35	3.44	9.15	48
Dun Troddan	18.3	4.3	7.62	49.7
Dun Dornaigil	13.1	2.44	6.7	37.2
Gurness	19.2	4.60	7.9	46
Dun Telve	18.2	4.30	10.22	47
1/15 model	1.3	0.31	0.63	48

Table 1. Dimensions of prototypes and model

4. Modelling process

In order to start the study in laboratory conditions of a relatively undefined problem, key characteristics of the original structures were chosen to be simulated. These include stonework and geometry, as well as loads similar to the forces exerted on the prototype throughout its life.

Particular attention was paid on the scaling of the stones in the models, which were all slivers from larger stones. It was important to achieve a compact bond and maximum contact similar to the high quality of the prototypes. The frictional properties of the stone were not scaled down for the models as the focus of this stage was on the performance of the form. The enormous variation of the contact between the blocks requires extensive tests that were out of the timeframe of this stage. The friction between the units is expected to be crucial in the distribution of loads in the radial sense too (Como, 2006). An attempt will be made in a next stage to simulate analytically the tests focusing on the complex interaction of the unilateral contact (Como, 2006) and using a multi-surface interface model for the stones and joint (Lourenço *et al.*, 2005).

A further attempt was made to improve contact using original methods, such as pinnings at larger joints, allowing compressive forces to distribute more evenly (Mundell *et al.*, 2010). Equally important was the similarity of material properties and masonry pattern between the two models.

Concerning loads, failure owing to dead load was not considered to be meaningful because it would not represent any real conditions. Settlement was selected because it can simulate the variable soil conditions some brochs are built on, like the sloped bedrock in Clachtoll or Dun Bharabhat. Equally important, however, such a test sets a straightforward relationship between the action and the test results, which can allow a mathematical model to be validated in the next simulation stage.

The 1:15 models were constructed according to the dimensions set out in Table 1. The key difference between the two models is the basal style: the ground-galleried 'Gurness' model has its walls beginning separately right from the base, with 'tie stones' placed across the gallery at every 90 mm level; the solid-based 'Dun Telve' model instead has a solid walled construction for the first 3 levels or 270 mm. The dimensions of the entrance passage were defined as 100 mm in width and 120 mm in height. The different construction types of the two models are illustrated in Figure 4.

5. Construction materials and re-creation of drystone fabric

The two models were constructed using Caithness flagstone, which has been used as a building material for millennia, including a number of broch sites. It is quarried from Spittal in Caithness from the Old Red Sandstone of Devonian age. It comes typically in flags that range from 20 mm to 80 mm in thickness and its clear bedding planes make it easy to split and shape by

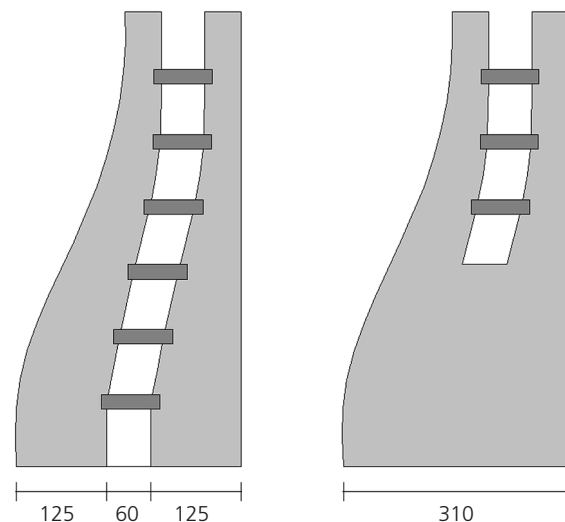


Figure 4. Cross-section of the ground-galleried 'Gurness' (left) and solid-based 'Dun Telve' (right) models

hand tools, making it ideal for model construction. Its material properties include a density of 2700 kg/m^3 , a compressive strength perpendicular to grain of 150 N/mm^2 , a bending resistance of 37.2 N/mm^2 and a slip resistance of 62 N/mm^2 , in wet conditions.

The walls of the broch models were constructed in horizontal courses like those in Dun Telve. Not only does this present a more regular and fine appearance of the stonework, but also it generally improves the point contact of the stones, essential for the integrity of the walls. It is also important for each stone to overlap with several others in order to distribute more evenly the forces within the wall and reduce the direct spread of a fault line, a layout that represents good original practice as well.

The placing of a stone upon another should ideally produce stable horizontal courses. This is difficult to achieve in reality, as stones with limited point contact can rock, necessitating the use of smaller stone shards, or pinning stones as they are known, packed into small cracks and voids to help larger stones rest more easily. The use of pinnings is a weakness in the construction method, as they are more easily dislodged by differential movement in the wall or by weathering, when not carefully packed.

The construction process is labour-intensive, as each stone had to be chipped and shaped from large stones in order to achieve the 1:15 scaling and to produce a high level of inter-locking (and, therefore, a strong and stable structure) through the bond of the blocks. This involved careful selection of stones that enabled inter-locking and as few gaps as possible.

Using the above techniques most of the key features outlined in the earlier sections were incorporated into the models. Figure 5



Figure 5. Completed 'Gurness' model

shows the quality of construction which represents successfully the prototype as ascertained by the industrial partners.

6. Test procedure

In order to capture the behaviour of the model during a test where very large deformations are expected, standard linear displacement measurement methods would need a complex set-up, which eventually would produce limited results. This is further complicated by the three dimensional nature of the structure, with its curved form and non-regular construction type. The diffusion of failure by large dislocations of the stones is also expected.

As a consequence, a three-dimensional (3D) laser scanner (Trimble GS101) was instead used to create a 3D point cloud of the model made up of thousands of individual points in space. The device was provided and operated by the industrial partner of the project, AOC Archaeology. The advantage of using the 3D scanner was the scale of data it produced. Instead of monitoring the movement of a limited number of fixed points, the 3D scanner allowed the global behaviour to be captured and key areas to be monitored.

The scanner was used after each base drop at key stages of the tests. Two stations were used in order to capture the complete deformation at each step. The images and data produced from the scanner were of high quality and the resolution was set to a density of 2 mm. The method allowed small dislocations and the opening of the crucial cracks to be monitored, and valuable data were collected that can be used for the analysis of localised failures.

The broch models were built on a plywood platform of medium roughness with a hinge running down the centre (Figure 6). Three hydraulic jacks were used to support the cantilevered half of the platform and subsequently apply and control the action of settlement to the model. As the cantilevered half of the platform rotated down, a gap opened between the two halves of the

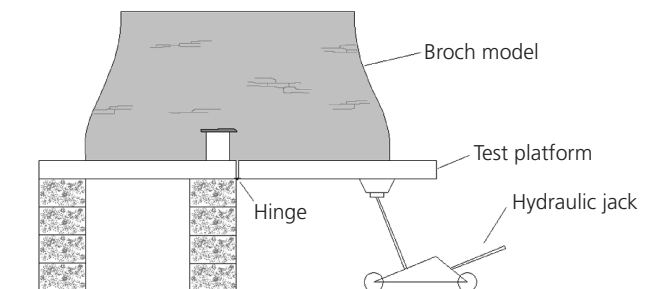


Figure 6. Test set-up (south elevation)

platform. To prevent stones falling into this gap a plastic membrane was put over this gap.

Settlement was applied in a stepped manner with the hydraulic jacks being operated at a safe distance, and after each application of settlement a laser scan was taken. The settlement was applied until final collapse of the broch structure.

7. Results and analysis

The orientation of the model is illustrated in Figure 7, with the settlement applied on the east face and the hinge running on the north-south axis.

7.1 Qualitative observations during tests on the ground-galleried 'Gurness' model

As settlement was applied to the model a crack gradually appeared in the South and North faces, beginning at the wall head, in line with the hinge of the base. These two cracks gradually propagated down the wall, following a vertical, direct path towards the line of the hinge. The amount of settlement applied was increased until the broch had effectively split into two separate halves that acted independently of each other.

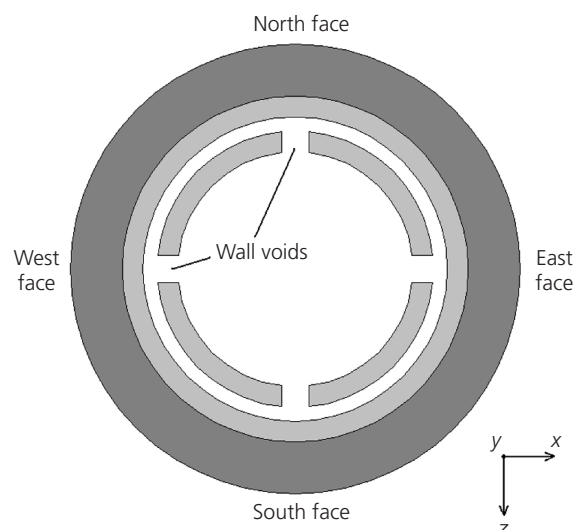


Figure 7. Orientation of model

The crack was clean in character (Figure 8), disturbing only a minimal amount of material, and as it propagated down the outer wall, on the inner face the wall voids at the north and south cardinal points expanded and the lintels spanning the internal wall voids began to fail as the distance they were spanning spread. The profile of the face under settlement rotated but, as settlement increased, no significant bulging in the profile itself was observed (Figure 10, see later).

The profile eventually rotated just beyond the vertical before collapse. The plan at the wall head also elongated under settlement, as the walls of the South and North face pulled inwards and the stones at the top of the wall on the East face, not being compressed by stones above them, began to slide (see later in Figure 10). The detachment of the two portions occurred at the drop between 80 mm and 90 mm settlement and ultimate collapse at 250 mm (with around 120 mm horizontal displacement of the base Figures 10 and 11 (see later)). This corresponds to a slope of 250/650 (half of ED) equal to 1:0.385 or an angle of 21°.

7.2 Qualitative observations at the solid-based 'Dun Telve' model

The behaviour of the solid-based model began in much the same way as the ground-galleried model with a crack appearing at the wall head in line with the N–S hinge. The crack was more diffuse, however, and with increased settlement the crack on the South face propagated towards the entrance as opposed to straight down. The more diffused nature of the cracks meant a much greater area of masonry was destabilised above the door. A smaller volume of material was lost at the East face directly above the applied settlement (Figure 9). The full detachment of



Figure 8. Collapse of ground-galleried 'Gurness' model (Southeast face)



Figure 9. Collapse of solid-based 'Dun Telve' model (Southeast face)

the two portions occurred at the drop between 100 mm and 130 mm. The final amount of settlement required to cause failure of the solid-based model was 280 mm (with around 200 mm horizontal movement at the base), or a slope of 280/650 = 1:0.431 or an angle of 23.3°.

8. Comparisons in the behaviour

Having observed the failure patterns of the models and the impact of the settlement on key features, the data from the laser scans were studied. The discussion highlights relationships between the settlement and deformation in the models and assesses the effect of the basal style on the structural performance.

8.1 Profile changes

Owing to the difficulties inherent in the non-regular construction process, the two models were not identical and significant differences in the overall plan dimensions were recorded by the laser scans, especially in the profile at the east face where settlement was being applied. To reduce the impact of the differences in the profile and make the data more comparable, the data were normalised by dividing the values with the maximum vertical and horizontal values in the initial data set for the profiles (Figure 10). The datum was taken at the wall-head. The graph clearly shows that, once normalised, the geometries match very well, indicating the effect of the high quality of workmanship achieved.

The graph also highlights the much greater stability in rotational settlement of the solid-based structure. Comparing the values of the normalised horizontal displacement at the wall-head for the solid-based model shows an increase of close to 100% before collapse over the ground-galleried design.

8.2 Change in plan

Figures 11 and 12 illustrate the change in plan during settlement of the two models (applied at the right-hand side). The datum is

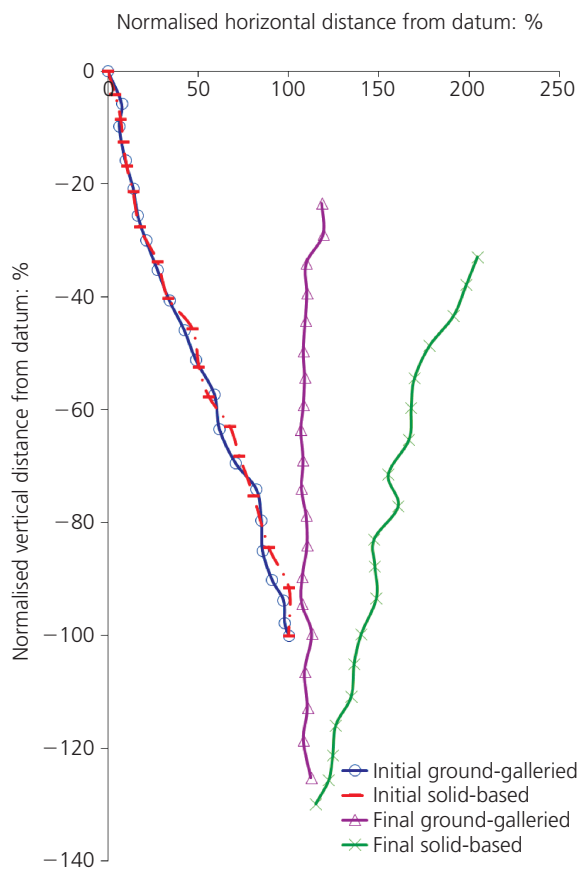


Figure 10. Normalised change between the initial and final profiles for both broch models

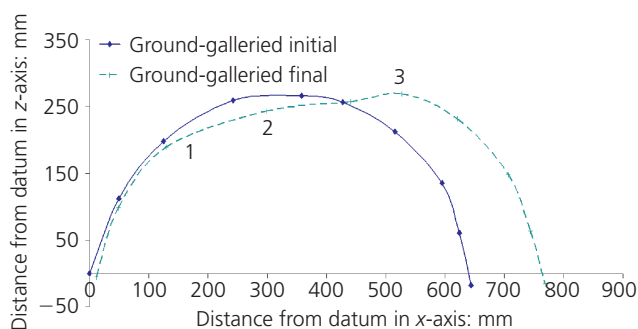


Figure 11. Change in plan at wall-head of internal wall of ground-galleried 'Gurness' model

taken at the wall-head from the void at the west face clockwise to the void at the east face. They indicate the plan of the half of the internal wall opposite the entrance passage before testing and the plan at which detachment of the halves occurred.

There are clear similarities in the trends between Figures 11 and 12: at failure they achieve similar maximum distance from the datum in the x -axis, of just over 750 mm, with the solid-based

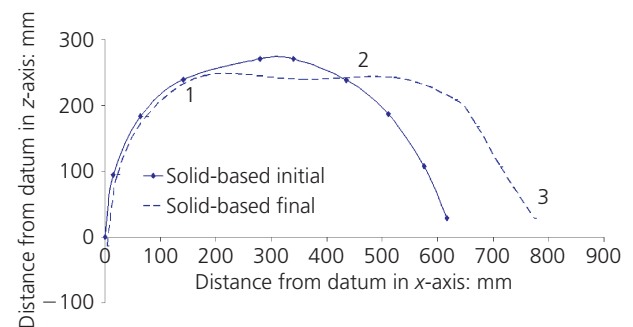


Figure 12. Change in plan at wall-head of internal wall of solid-based 'Dun Telve' model

model having a slightly larger displacement due to the greater amount of settlement it undertook before failure. A squeeze of the plan is clear in the final state, from point 2 in the ground-galleried (Figure 11) and from point 1 onwards in the solid-based (Figure 12), where the elongation of the plan caused the external walls to lean inwards. Eventually, the deformation produced slippage between the stones and, ultimately, a failure plane that propagated from the wall-head down.

There are, however, some significant differences in the change in plan between the two models. The curvature at failure in Figure 11 between points 1 and 2 is far smoother than that in Figure 12 (Dun Telve), which has a clear change in curvature at point 1, making the behaviour of the ground-galleried broch (Gurness) more uniform up to this stage, and again indicating the more localised nature of the crack propagation. The large flat area of the solid-based plan, on the other hand, indicates how the failure had an impact across a much larger area of the wall.

Figure 12 clearly shows that the solid-based model flattens, while the ground-galleried broch (Figure 11) bulges at point 3. This suggests that there is a rotational component in the ground-galleried mode of failure, where the inner leaf of stonework is twisting round due to uneven settlement that is not present to the same extent in the solid-based model, pointing to the conclusion that, once detachment of the two halves had occurred, the ground-galleried model is more unstable.

Finally, the extreme displacement of the final plan (Figure 12) at point 3 shows another clear change in curvature caused by a greater relative displacement of the wall at this point. This suggests that the internal wall was sliding into the gallery at this point and could be part of what triggered the final collapse.

Regarding the range of settlement, it is necessary to relate the rotation at the induced settlement with the resistance of the drystone masonry, as expressed by the angle of friction. In order to characterise friction of the Caithness flagstone in these conditions, a series of simple incline plane tests were set up to evaluate the friction angle or the coefficient of friction, μ

(tangent). Ten specimens of the sizes used in the settlement tests (10 cm long average) were placed on a rather flat sample of the same stone, then they were slowly tilted until the top blocks started to slide. The tests were repeated three times for each face of the blocks and the normal distribution of the total of 60 tests gave an average friction angle of 37.9° (or $\mu = 0.79$).

The comparison with the behaviour of the drystone masonry in the model shows that the circular structures fail earlier at 21° (gallery) and 23.3° (solid-based). Although the load of the structure provides high compressive forces that increase the shear strength of the masonry, the earlier failure is a clear effect of the weight applied eccentrically at the moment of maximum rotation of the platform. Failure is triggered by displacement of the upper rows which are less confined in the radial and hoop directions by compressive forces. Eventually, the in-plane component of the load increases with rotation and exerts a lateral force that overcomes the elevated shear strength and causes the propagation of failure at a lower friction angle.

9. Behaviour of brochs and effect of basal style

The general behaviour of the two models during the settlement process was reasonable and the final collapse patterns achieved bear a strong resemblance to the remains found at sites such as Clachtoll or Dun Carloway. The frictional forces between the stones can be overcome with increased tilt until a discontinuity between the stones is formed, at which point local failure has occurred and the stresses are shed elsewhere.

The collapse pattern also demonstrated that detachment of a failing zone can occur rapidly, relieving the remaining structure from strain. Many brochs have collapsed gradually following localised failure, and the tests demonstrate that significant portions can remain intact, as happened with the best preserved ones. The final value of settlement, however, is unrealistic ($130 \text{ mm} \times 15 = 1.95 \text{ m}$), but the broch can be considered to have failed once the detachment has been complete.

The behaviour of the outer leaf of the wall at the north and south face supports the theory of the 'tie stones' effectively being props between the two walls, as large areas of masonry disturbed by the settlement tended to fall inwards compressing the structure. Archaeological evidence at Dun Telve, where the upper galleries have been 'crushed together' (MacKie, 2007) also supports this.

The incorporation of the different basal styles into the two models clearly had an impact on the behaviour of the two brochs under settlement. While the ground-galleried model split down the axis of rotation, not significantly affecting the area of masonry above the door, the solid-based model saw a much wider area of impact, and caused the disturbance of the stonework directly above the door. Once the structure had effectively split in two, the solid-based halves also showed much greater independent stability, with much less stone lost when the final collapse occurred.

The reasons behind the different behaviour patterns can be explained by studying the effect of the solid-based construction on the global behaviour of the structure. The use of a solid base to over a third of the complete wall height means the two walls above, although divided by a gallery, act in unison with one another to a far greater extent than shown in the ground-galleried model. The centre of gravity of the combined double-wall is kept within the base of the footing for longer period. Conversely the ground-galleried broch walls did not act in unison, and collapse occurred once the centre of gravity of the outer wall reached outside the footing.

The more unitary behaviour of the solid-based broch had the effect of distributing the forces more evenly within the wall, causing the disturbance of a much larger area of masonry on the North and South face, although this occurred at a later stage.

The higher stiffness of the basal portion of the solid-based model also explains why the crack in the north face propagated towards the entrance, as this was a very weak point in the structure, instead of towards the axis of the hinge, as in the ground-galleried model.

10. Conclusion

The scale models enabled a detailed exploration of the construction process and its effect on the geometry. The settlement also provided valuable information on the development of failure and detachment of the collapsing portion. Through erecting and testing to destruction the two 1:15 scale broch models of 'Gurness' and 'Dun Telve', a clear distinction between the failure modes of the two base styles was established.

The evidence from the two tests undertaken shows brochs to be substantial structures, capable of withstanding large amounts of settlement before failure and ultimate collapse. This clearly suggests that settlement alone is not a major factor in the failure of brochs. Other factors, such as gradual decay owing to neglect or deliberate destruction by human hand must, therefore, have been equally important in the deterioration of brochs from complete structures to the ruins most are today. The whole process might have been accelerated by a simultaneous failure of other elements, like the roof or internal platforms.

With the two tests completed, the next stage will be to attempt to reproduce the results using numerical modelling. Smaller scale tests into the behaviour of drystone construction, and in particular concentrating on the point contact of the stones, would be useful in defining the material properties for numerical analysis.

Another valuable line of research is the effect of the PWB on the stability of broch structures. The value was a constant during these tests, but further experiments could be done to ascertain the effect of its variation on structural stability.

Acknowledgements

AOC Archaeology are the industrial partners of the project and they are thanked for supplying the stone and the operation of the

3D scanner that enabled the desired level of measurable data used (in particular John Barber, Graeme Cavers and Gemma Hudson). Their comments on the pattern of the ruins were valuable for the interpretation of the collapse process. Moreover, Alistair Craig and Malcolm Cruickshank from the Workshop and Rachel Travers, media technician, all from the Department of Architecture are warmly thanked. All photographs of the tests are credited to Rachel Travers.

REFERENCES

- Armit I (2003) *Towers in the North, The Brochs of Scotland*. Tempus Publishing, Gloucester, UK.
- Armit I and Fojut N (1998) *Dun Charlabhaigh and the Hebridean Iron Age*. Urras nan Tursachan, Scotland, UK.
- Barber J (2009) Discussion of Broch construction. *Towards An Improved Understanding of the Engineering of Brochs*, 2009. See <http://sites.google.com/site/brochgroup/home> for further details (accessed 01/03/2011).
- CANMORE (2011) CANMORE, online database from the National Monuments Record, RCAHMS. See <http://canmore.rcahms.gov.uk> (accessed 01/03/2011).
- Como MT (2006) Analysis of the statics of the Mycenaean Tholoi. *Proceedings of 2nd International Congress on Construction History, Queen's College, Cambridge University, UK*. Construction History Society, Cambridge, UK, pp. 777–790.
- Curle AO (1916) An account of the ruins of the broch of Dun Telve, near Glenelg, excavated by H.M. Office of Works in 1914. *Proceedings of Society of Antiquaries Scotland* **50**: 241–254.
- Fojut N (1981) Is Mousa a broch? *Proceedings of Society Antiquaries of Scotland* **111**: 220–228.
- Harding DW (2000) *Dun Bharabhat, Cnip: An Iron Age settlement in west Lewis*. Department of Archaeology, University of Edinburgh, Edinburgh, UK.
- Harding DW (2004) *The Iron Age in Northern Britain: Celts and Romans, Natives and Invaders*. Routledge, London, UK.
- Lourenço PB, Oliveira DV, Roca P and Orduña A (2005) Dry joint stone masonry walls subjected to in-plane combined loading. *Journal of Structural Engineering, ASCE* **131**(11): 1665–1673.
- MacKie E (1974) *Dun Mor Vaul – An Iron Age Broch on Tiree*. University of Glasgow Press, Glasgow, UK.
- MacKie EW (2002) *The Roundhouses, Brochs and Wheelhouses of Atlantic Scotland C.700BC-AD500 – Architecture and Material Culture Part 1 The Orkney and Shetland Isles and Part 2 (I), (II) The Northern and Southern Mainland and The Western Isles*. British Series 342. Archaeopress, Oxford, UK.
- MacKie EW (2007) *The Roundhouses, Brochs and Wheelhouses of Atlantic Scotland C.700BC-AD500 – Architecture and Material Culture Part 1 The Orkney and Shetland Isles and Part 2 (I), (II) The Northern and Southern Mainland and The Western Isles*. British Series 342. Archaeopress, Oxford, UK.
- Martlew R (1982) The typological study of the structures of the Scottish Brochs. *Proceedings of Society of Antiquaries Scotland* **112**: 254–276.
- Mundell C, McCombie P, Heath A, Harkness J and Walker P (2010) Behaviour of drystone retaining structures. *Proceedings of the Institution of Civil Engineers – Structures and Buildings* **163**(1): 3–12.

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